#18608 08MV-22

Motion Base Simulation of a Hybrid-Electric HMMWV for Fuel Economy Measurement

Mark Brudnak, Mike Pozolo, Matthew McGough
U.S. Army RDECOM-TARDEC

Todd Mortsfield, Andrey Shvartsman
DCS Corporation

Richard Romano
Realtime Technologies, Inc.

ABSTRACT

This paper describes a human-in-the-loop motion-based simulator which was built to perform controlled fuel economy measurements for both a conventional and hybrid electric HMMWV. The simulator was constructed with a driver's console, visualization system, and audio system all of which were mounted on the motion base simulator. These interface devices were then integrated with a real-time dynamics model of the HMMWV. The HMMWV dynamics model was built using the real-time vehicle modeling tool SimCreator®, which, in turn was integrated with two powertrain models implemented with Gamma Technologies GT-Drive® product. These two powertrains consisted of a conventional configuration and a series hybrid-electric configuration. These models were then run on four different standard Army fuel consumption courses to replicate tests which had previously been conducted at the proving ground. Experiments were performed for varying speeds with two experienced proving ground drivers. This paper describes the design and implementation of the simulation environment, the execution of the experiment and presents some results measured in the experiment.

INTRODUCTION

HEVEA PROGRAM

The US Army Tank Automotive Research Development and Engineering Center (TARDEC), along with the Office of Naval Research (US Marine Corps) are collaborating on a Hybrid Electric Vehicle Experimentation and Assessment (HEVEA) program. One end product of the HEVEA program will be an updated standard test operating procedure (TOP) for measuring fuel economy of military vehicles (the current TOP may be found at [3]).

Hybrid vehicle fuel consumption characterization is an area of vehicle performance that requires a systematic approach for evaluation. Procedures available for conventional vehicles, when applied to hybrid systems, often do not yield consistent results. This is due to multiple energy sources for propulsion, and system control strategies that employ energy recovery during braking and downhill descents. The updated test operating procedure will be independent of propulsion system type and therefore applicable to current and future military vehicles with advanced propulsion systems.

Aberdeen Test Center (ATC) is participating in the TOP development providing instrumentation, field test support, data collection and analysis. TARDEC has supplied an XM1124 hybrid-electric HMMWV equipped with Li-ion traction batteries, along with a conventional M1113 HMMWV as the initial test vehicles for the methodology study. These two vehicles were modeled for the DCE-TOP experiment.

MOTIVATION AND PURPOSE

As part of the Power & Energy (P&E) program, TARDEC has been building, developing and using human-in-the-loop simulation technology for the purposes of measuring military vehicle duty cycles. We have called these duty cycle experiments (DCEs). This paper describes an experiment which was executed to evaluate TARDEC's ability to use motion simulators to measure the fuel economy of hybrid electric vehicles according to the procedures developed under the HEVEA program. This experiment, called duty cycle experiment – test operating procedure (DCE-TOP), has attempted to replicate the APG test in every pertinent detail.

The remainder of the paper first lays out the experimental design. It then describes the technical design and implementation of the simulator to include the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **18 JAN 2008**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Motion Base Simulation of a Hybrid-Electric HMMWV for Fuel Economy Measurement**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Mark Brudnak; Mike Pozolo; Matthew McGough; Todd Mortsfield; Andrey Shvartsman; Richard Romano**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000**		8. PERFORMING ORGANIZATION REPORT NUMBER **18608**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM/TARDEC** 11. SPONSOR/MONITOR'S REPORT NUMBER(S) **18608**
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **Presented at the SAE 2008 World Congress, April 14-17, 2008, Detroit, Michigan,, The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

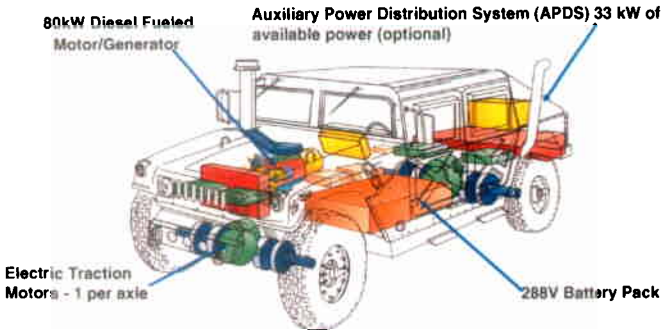

Figure 1. Diagram of the XM1124 Hybrid Electric HMMWV.

Figure 2. M1113. [source: AM General. Permission allowed for non commercial uses.]

integration of a real-time vehicle dynamics model with a real-time version of a power-train model. It next describes some of the major components in the simulator. Finally it presents some experimental results and offers some conclusions.

EXPERIMENT DESIGN

As stated earlier the intention of DCE-TOP was to evaluate the utility of human-in-the-loop simulation in the measurement of fuel economy of a hybrid-electric vehicle. In order to demonstrate this utility, TARDEC designed and executed this experiment to replicate measurements done at Aberdeen Proving Ground (Aberdeen, MD). In the Aberdeen-designed experiment there were five experimental variables. The first variable was the vehicle under study. They ran both a conventional HMMWV (M1113) and a series hybrid-electric HMMWV (XM1124) (See Figures 1 & 2). They were run in a two-vehicle convoy so that they experienced the same circumstances with regard to speed, terrain, temperature, etc. The M1113 served as the control in the experiment. The second variable was terrain. APG chose to evaluate the fuel economy on four different courses which represented a reasonable range of grades and pavement types. These terrains were referred to as Harford Loop, Perryman Paved, Munson Standard Fuel Course (SFC), and Churchville B; they will be described later in this paper. The third experimental variable was the vehicle speed which was varied in 5 mph (8 kph) increments on all courses except for Harford Loop. The fourth experimental variable was the initial battery state of charge (SOC) of the XM1124 which was set either high (approximately 80%) or low (approximately 50%). The fifth variable was the vehicle operator; each vehicle, speed, terrain and SOC combination was run with at least two different operators. In this way the experiment results were not dependent on the particulars of one driver's driving method. These variables are summarized in Table 1.

Table 1. Experimental variables.

Variable	Scope	Values
Vehicle	-	M1113, XM1124
Terrain	-	Harford Loop Perryman Paved Munson SFC Churchville B
Speed	Not varied for Harford Loop	Perryman: 10 – 60 mph Munson: 10 – 30 mph Churchville:10 – 25 mph
Driver	-	A, B
Initial SOC	XM1124	High: ~80% Low: ~50%

In the TARDEC implementation of DCE-TOP we attempted to replicate the design of the APG experiments. First we implemented a real-time vehicle dynamics model of the HMMWV chassis to include its chassis, suspension, tires, and steering system. Coupled with this dynamics model we developed two power train models, one for the conventional M1113 and one for the hybrid XM1124. Second, we built models of the four terrains which were run at APG. Third our experimental design sought to match the speed ranges and increments which were run at APG. Fourth, because we had a modeled power train, which modeled the SOC as an independent state, we were able to precisely set the initial SOC either a high or low value. For high we used 80% and for low we used 50%. Finally for driver variation, we recruited as participants two experienced APG drivers.

As mentioned earlier one of the vehicles evaluated was a conventional M1113 HMMWV. This vehicle was modeled with a GVW of 5,216 kg (11,500 lbs). The weight was distributed front to rear in a 40/60 proportion. The tires were modeled at 276 kPa (40 psi) in the front and 344 kPa (50 psi) in the rear. The XM1124 is a hybridized version of the M1113. So the chassis parameters and dynamics as modeled were the same for this vehicle.

The DCE-TOP experiment was conducted during the week of February 12-16, 2007. In all there were 166 runs completed and all planned runs were completed.

TERRAIN DESCRIPTIONS

We next describe the four terrains on which the experiment was executed. We begin with the simplest. The Perryman Paved terrain is a level, straight, paved course which is approximately 2 miles (3.2 km) long with flat turn-a-rounds at the ends. A picture of the Perryman Paved course is shown in Figure 3. (The course is fully

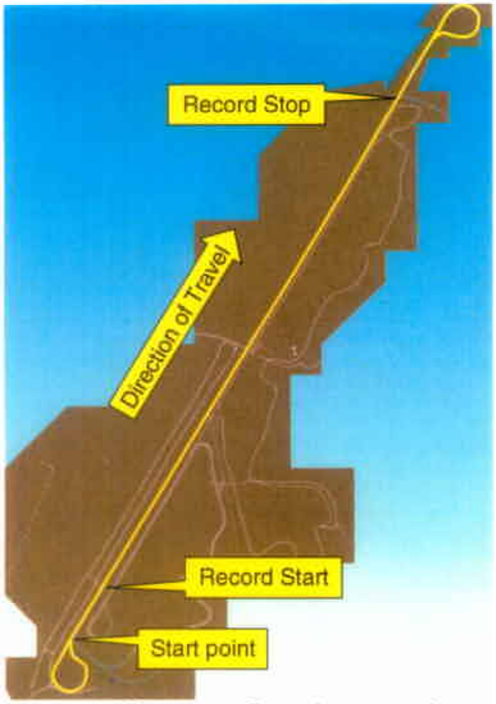

Figure 3. Perryman Paved course shown in yellow.

described in an APG TOP [2]). At the start of a run the operator would be stationary. He would then accelerate up to the desired speed by the time he reached the “Record Start” point. After that point he would hold the vehicle at a constant speed until he reached the “Record Stop” point at which time the simulation was stopped. Unlike the APG runs, all of the simulation runs were done in a South-to-North direction. The actual length of the record was over 2.4 km (1.5 miles) of the course. Speeds on this course varied from 10 mph (16 kph) to 60 mph (96.6 kph) in 5 mph (8 kph) increments.

The other paved course was the Harford Loop. This course, unlike the other three, is not APG-owned. Rather it is a closed circuit of public roads in Harford County, MD. The roads are all paved, have posted speed limits and are open to normal traffic. The country side in which the roads reside is rural. There are four turns in the course, each at an intersection. Three of these intersections are regulated with stop signs and one is regulated with a stop light. An illustration of the course is shown in Figure 4. For this experiment the course was driven in a clockwise sense. Each run began at the “tail” in the south-east corner on SR-136 driving North. The operator then proceeded to SR 440 turning left and proceeding West. The operator then successively proceeds through SR-543, SR-165, and SR-136 successively making right turns and the course ends at the intersection of SR-136 and SR-440. The total length of the course is approximately 17.6 mi (28.3 km). The course varies in elevation as much as 463 ft. (141 m), it contains grades from -15% to +18% and has a mean absolute grade of 3.3%. Because the course consists of public highways, the speeds were regulated by the posted speed limits which varied from 30 mph (48 kph) to 50 mph (80 kph).

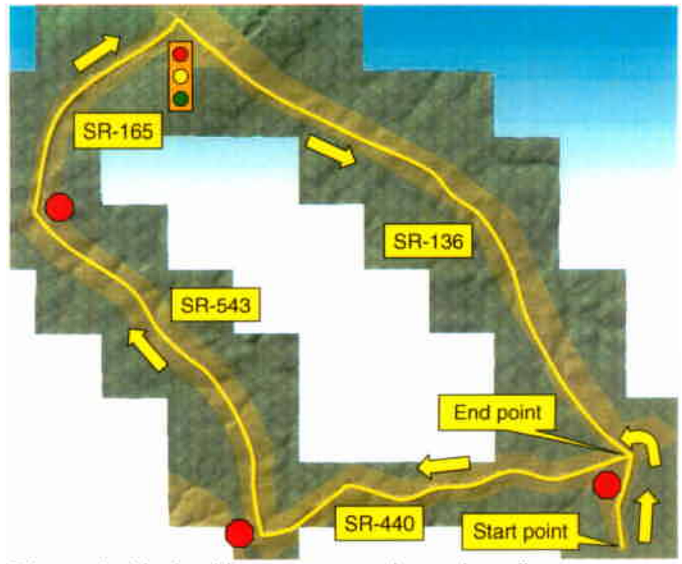

Figure 4. Harford Loop course shown in yellow.

The third course used for this experiment is the Munson Standard Fuel Course (SFC) at APG. The Munson SFC course consists of a loop of approximately 1.67 miles (2.7 km) situated at the Munson Test Area (MTA). The course is composed of both on-road and off-road surfaces. The off-road portion is driven on the Munson Gravel course. The course also traverses the gradeability portion of the MTA. For each loop the vehicle makes two passes by the gradeability area. On the first pass it ascends an approximate 6% slope and descends a 5% slope. On the second pass the vehicle ascends 40 ft. (12 m) up a 30% slope and descends a 15% slope. The speeds on the course varied from 10 mph (16 kph) to 30 mph (48 kph) in 5 mph (8 kph) increments. It is difficult to maintain the target speed on

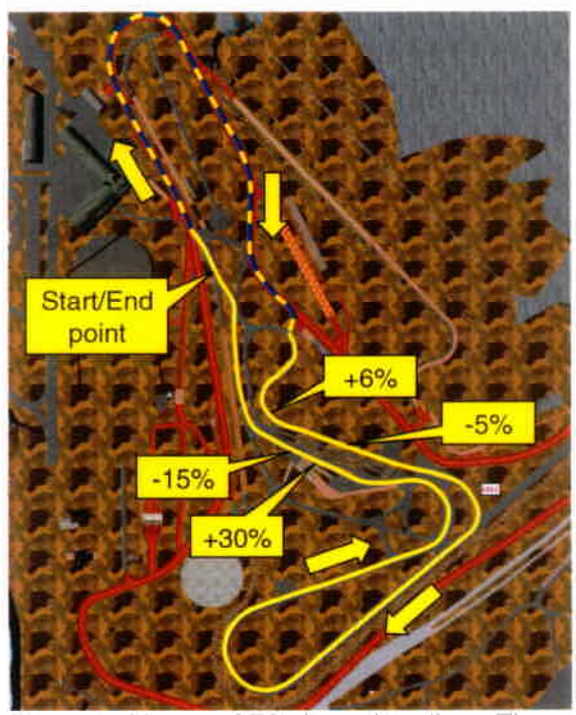

Figure 5. Munson SFC shown in yellow. The off-road segment is dashed.

the 30% grade, so drivers tended to makeup time in other portions of the course to make the average loop speed correct. A Figure illustrating the course is shown in Figure 5. The total elevation change over the course is 42 ft. (12.7 m), its grades range from +30% to -15% and it has a mean absolute grade of 2.5%.

The fourth course used in the experiment was a hilly cross-country course called Churchville B which is situated at the Churchville Test Area in close proximity to APG. The course is described in the Government publication [2]. The course is shown in Figure 6. Churchville B is a 3.7 mile (6 km) closed loop course. Its grades vary from -23% to + 29% and it has a mean absolute grade of 8.9%. The course has four stop signs positioned at the bottom of its (29%, 14%, 19% and 14% grades). These are positioned so that all vehicular momentum will be dissipated in braking at the bottom of these hills. Furthermore, the North-East section of the course contains four passes of moguls. There are 39 moguls in all and they range in height from 15 to 20 inches (38 to 51 cm). These moguls dramatically increase the ride severity in these sections and therefore cause the drivers to reduce their speed when going down hill. It is difficult to maintain a constant speed on the course due to the steep grades. Like the Munson SFC course, the drivers "made up" lost time on other sections of the course. The course was run at speeds ranging from 10 mph (16 kph) to 25 mph (40 kph) in 5 mph (8 kph) increments.

SIMULATION ARCHITECTURE AND DESIGN

In this section we discuss the design and construction of the simulator which was used to conduct the experiment. We begin with a description of the top-level design. We then discuss in detail several of the key components used to implement the experiment.

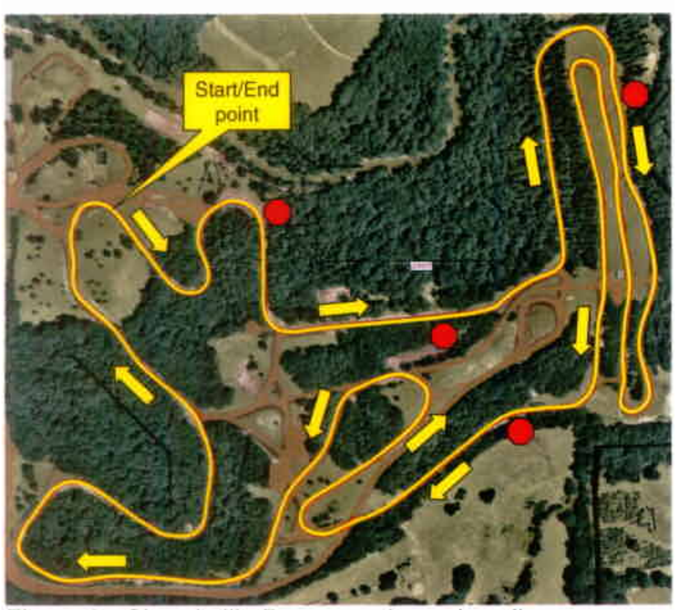

Figure 6. Churchville B course shown in yellow.

TOP-LEVEL DESIGN

The simulator designed for this experiment consists of a HMMWV driving station, display system, and sound system mounted on a motion base simulator. A picture of this setup taken during the experiment is shown in Figure 7. The motion base simulator is the Ride Motion Simulator (RMS). The driver interface is implemented as a HMMWV built-up cab (BUC) and is shown in Figure 8. The displays were implemented with three Samsung® SyncMaster™ 226BW displays which are 22" 1680x1050 LCD flatpanels. They are shown in Figure 9. The displays were driven by NVIDIA 8800 GTX video cards. The software which drove the simulator was implemented using a simulation integration framework called SimCreator®. Using SimCreator®, the software was developed and distributed for execution over six computers, five of which were PCs running Windows XP Pro® and one of which was a dual-processor iHawk® running RedHawk® Linux. One other computer was used to record video of the experiment using a tool called SimObserver®. Finally one PC was used to monitor and control the motion base simulator.

Functionally, the software executed in real-time and data flow among the components was managed by SimCreator® using either shared memory and UDP/IP transfer data among components. The principal software components were the dynamics, BUC interface, motion base interface, sound generation, visual channel drivers, stealth viewer (for recording), and SimObserver®. The functional flow of information between these components is illustrated in Figure 10. There we observe that the information flow begins with the BUC which generates analog signals sensing the


Figure 7. Simulator used for the DCE-TOP experiment.

Figure 8. HMMWV BUC used for the experiment.

Figure 9. Displays used for the experiment.

steering, brake, accelerator, and gear positions. These data flow to the vehicle dynamics component (which runs on the iHawk). The vehicle dynamics uses these commands to generate power train torques, brake forces, and steering forces which affect the vehicle's instantaneous acceleration, and subsequently velocity and position. These data along with powertrain torque and RPM are used to feed all of the other subsystems. The steering torque and vehicle speed are fed back to the BUC to generate wheel torques and drive the speedometer. The vehicle position and orientation are used to update the eye point positions in the three visual channels and of the stealth view. The acceleration, and angular velocities and positions are fed to the OverTilt® washout algorithm which generates suitable commands for the motion base. These motion commands are transferred to the motion controller via a SCRAMNet® reflective memory network. The engine torque and RPM are also fed to the audio generation component for the rendering of vehicle sounds. Finally, the video generated by the stealth view, three camera views and various text information are fed to the SimObserver® component for documentation of the experiment run.

VEHICLE DYNAMICS

For this experiment two HMMWV configurations (the M1113 and the XM1124) were modeled in SimCreator®: SimCreator is a graphical modeling software package described by Romano [9]. Models are constructed by connecting components in a block diagram styled approach. TARDEC has previously modeled other vehicles using SimCreator [4,5,7,8]. The first step in creating the HMMWV models was to convert by hand a similar HMMWV configuration from DADS. The DADS software package is a commercially available product

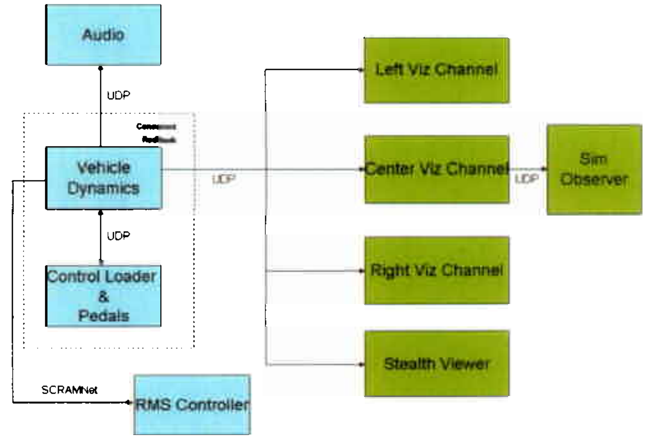

Figure 10. Top-level architecture.

through LMS International (formerly CADSI). A corner module was first generated in SimCreator® that could be used to represent each of the four corners of the HMMWV. The corner module contained four bodies that represent the lower control arm, upper control arm, wheel spindle, and wheel. The corner is shown in Figure 11. Four corner modules were combined with a two-body model of the front anti-roll bar as well as a three-body model of the pitman arm steering system to form the complete HMMWV. The complete model contained 22 bodies.

In addition to being a 22-body mechanical system, the model also incorporates all of the necessary force generating systems such as tires, power train, brakes, suspension, and aerodynamics. The tire serves as the sole interface between the terrain and the vehicle. It is responsible for generating vertical, longitudinal and lateral forces and yaw and roll moments at the spindle of each corner. These forces are developed based on well known tire modeling practices based on tire deflection and slip. The rolling resistance of the tire was assumed to be 1.5% of the vertical load on the tire. The power train model was split between SimCreator® and GT-Drive®. SimCreator handled the transfer case, front and rear differentials and the reduction hubs. GT-Drive handled the rest of the power train for both variations. The details of the GT-Drive model are discussed in the next section. The brakes were modeled differently for the XM1124 and the M1113. The conventional M1113 brakes were modeled as hydraulic disk brakes. The hybrid XM1124 brakes were a mixture of powertrain regeneration and the service brakes. The load was shared between these two braking systems based on the severity of the braking event. Lighter braking events were handled exclusively as regeneration events, while hard braking was split between regeneration and conventional brakes. The HMMWV suspension consists of a damper in-line with a coil spring. The damper on the HMMWV contains the jounce and rebound stops. The aerodynamic drag of the HMMWV was modeled as a simple function of the velocity squared, frontal area and the drag coefficient.

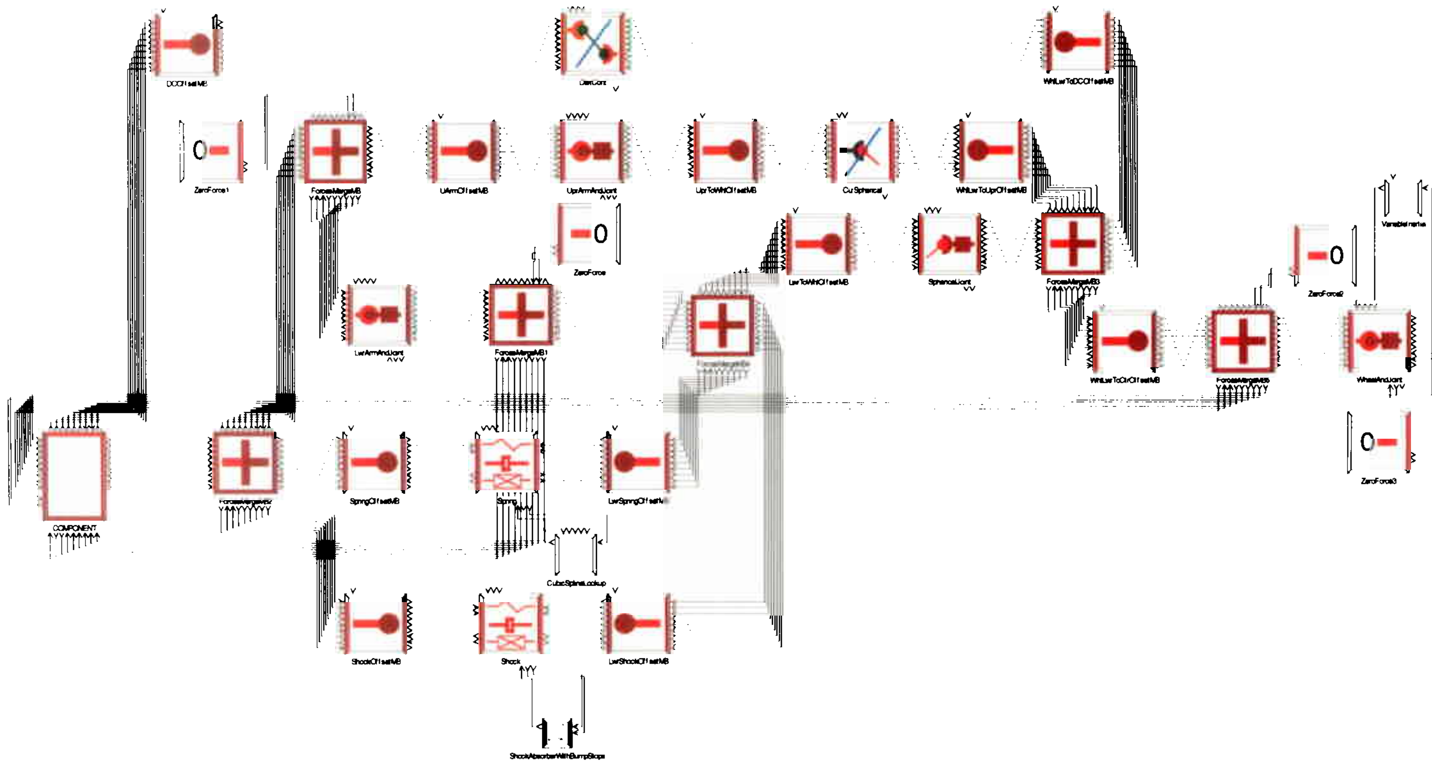

Figure 11. Vehicle dynamics model of one corner of the HMMWV suspension as implemented in SimCreator®.

Development of the model structure was very quick; however, values for the various parameters then had to be extracted from the DADS model. This process was labor intensive and took significant time. To verify the translation's accuracy all kinematic parameters were verified against those developed by Aardema [1]. Other parameters were verified against vehicle drawings. Since the XM1124 and M1113 models were both operating at their Gross Vehicle Weight (GVW), it was found that some suspension and tire data were not originally configured for dynamic load values at and above the GVW. Extensive work therefore focused on extending tabular tire data where necessary to account for the higher forces.

POWER SYSTEM DESIGN

OVERVIEW - GT-Drive, part of Gamma Technologies GT-ISE integrated engine, powertrain and vehicle simulation software [6], was used to model both conventional diesel-mechanical and series hybrid-electric powertrains for this experiment. The M1113 conventional powertrain consists of a GEP 6.5Liter turbo-diesel engine coupled through a GM 4L80E automatic transmission and a 2-speed transfer case to the axles (Figure 12). The XM1124 series-hybrid powertrain consists of a Peugeot 2.2Liter turbo-diesel engine driving a generator, which is connected through a Saft LiON battery pack to a traction-motor driving each axle (Figure 13). The UQM SR-286 is used for both generator and motors.

Complete GT-Drive models of the M1113 conventional and XM1124 hybrid HMMWV vehicles were first developed, and validated against proving-ground test data. The GT-Drive vehicle and driver components were then removed, and a wiring harness was established to interface with the more detailed SimCreator® vehicle-dynamics model and the human driver. The powertrain model was then compiled to run with Gamma Technologies Real-Time solver for use in the human-in-the-loop co-simulation.

Powertrain Components

Engines – The GEP and Peugeot engine components are map-based models with lookup tables for mechanical-output, fuel-consumption and heat-rejection. This level of model is appropriate for evaluating vehicle performance on long-duration driving cycles [6]. The mechanical output map includes both lug and motoring friction curves, based on speed and throttle position. Fuel consumption and heat rejection rate maps are based on engine speed and mechanical output. These maps were generated from available test data using a bivariate 2nd order fit to cover the complete RPM-BMEP range (Figure 14). A first-order time constant was used to simulate turbocharger-lag on throttle advance. Separate idle and over-speed governor controls were implemented for the GEP engine. The Peugeot engine controls are part of the hybrid control system. Accessory loads including the cooling fan are engine driven in the M1113, and electrically driven in the XM1124.

Transmission – The 4L80E automatic transmission is modeled with gear-box, torque-converter, and lockup-clutch components. The gear box includes mechanical efficiency and spin losses for each gear ratio. The torque-converter is modeled with table lookups for input capacity-factor and torque-ratio vs. speed ratio.

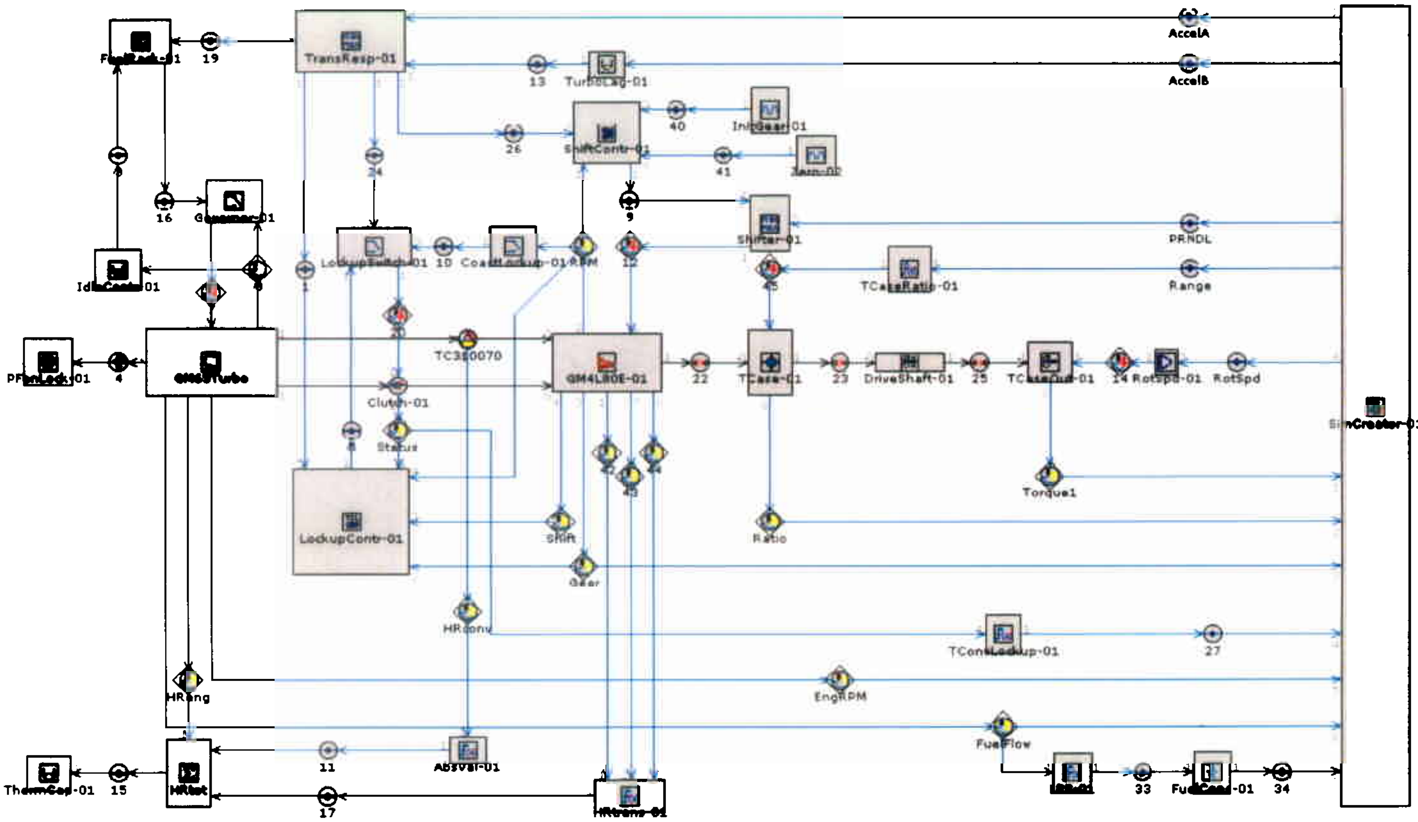

Figure 12. Conventional power train of the M1113 as modeled in GTDrive®.

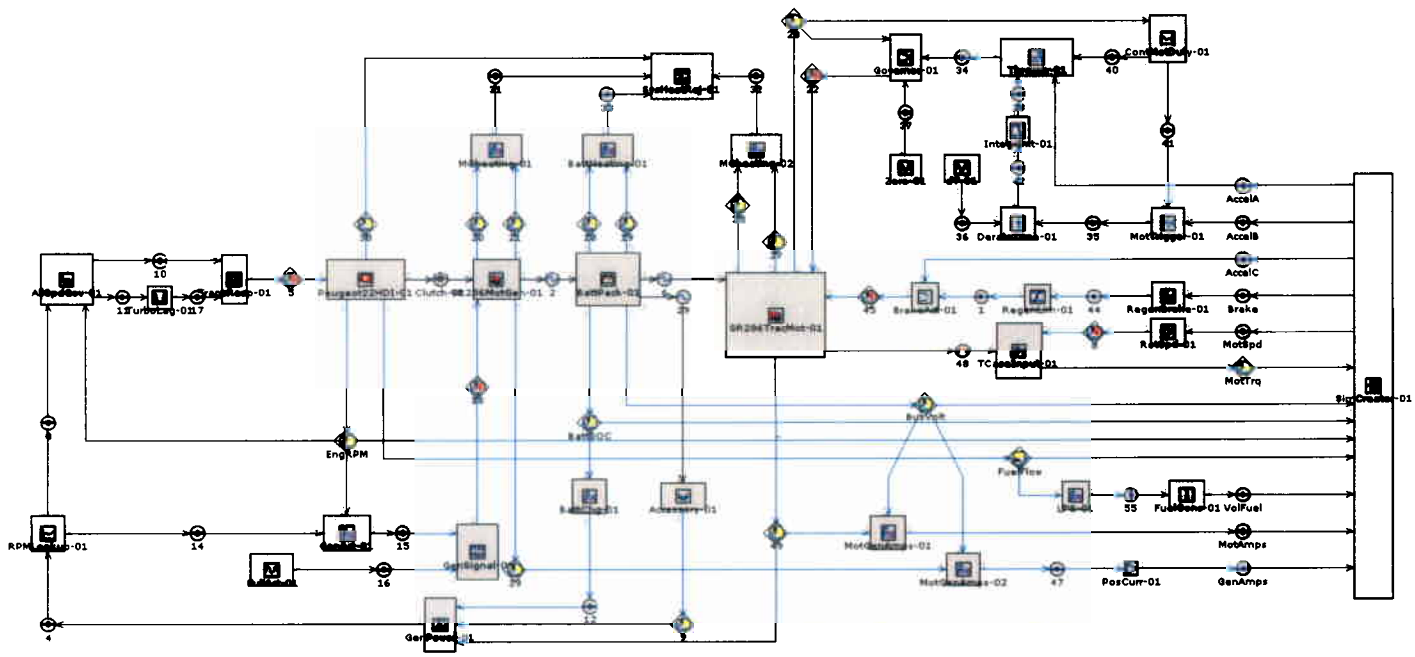

Figure 13. Hybrid-electric power train of the XM1124 as modeled in GTDrive®.

Transmission shifting and converter lockup schedules are based on transmission output rpm and throttle position. Use of output rpm makes these schedules independent of the transfer-case range selected.

Electric Machines – The UQM SR286 motor/generator components are map-based models with lookup tables for shaft torque and electro-mechanical efficiency based on speed and actuation. Efficiency maps were generated from available test data using a bivariate non-linear fit to cover the complete speed-torque range (Figure 15). No component to explicitly model power-electronics is currently available in GT-Drive, so an assumed efficiency value was used as a map-multiplier. Generator and motor operation are modeled somewhat differently. The engine-generator match for the XM1124 has engine torque as the limiting factor, so the engine lug-curve is substituted for the generator torque curve.

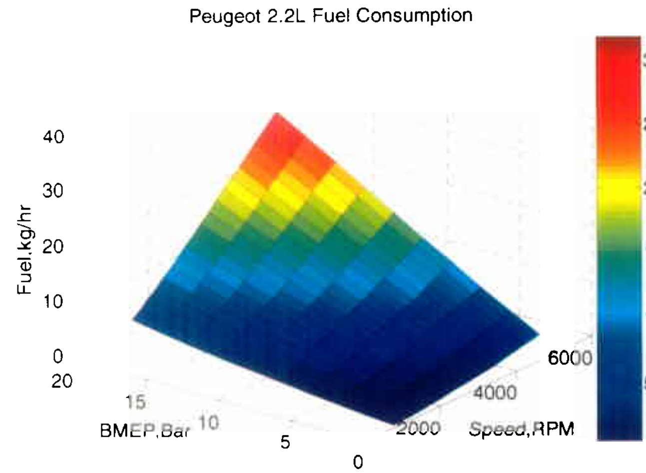

Figure 14. Fuel consumption map for the XM1124

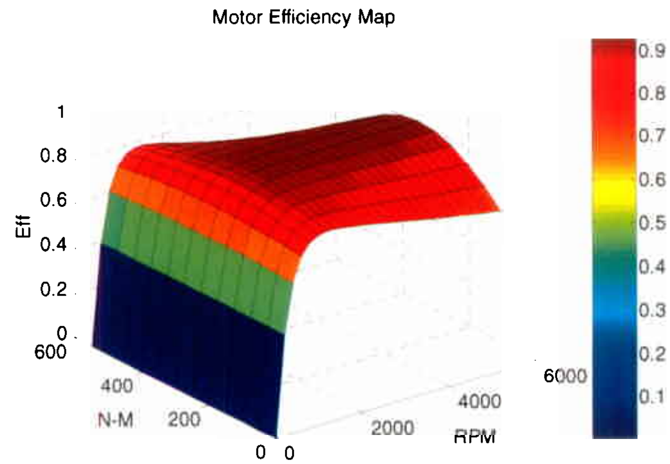

Figure 15. Efficiency map for the XM1124 electric motor.

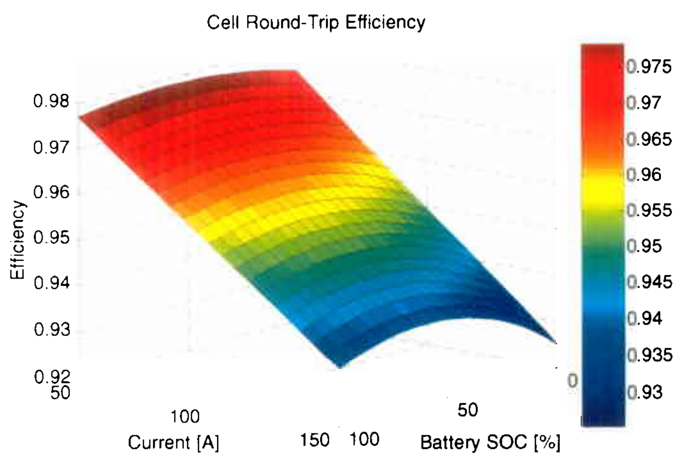

Figure 16. Efficiency map for the XM1124 battery.

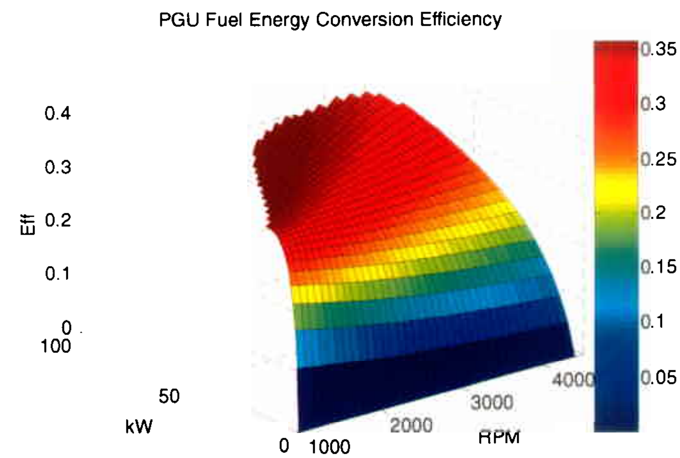

Figure 17. Efficiency map for the XM1124 PGU.

The traction-motors include torque-curves for peak and continuous motor duty, and a regenerative braking curve. The XM1124 requires peak motor torques for acceleration and maximum gradeability. Driver pedal inputs up to the peak duty curve are allowed for short durations, but are forced to return to the continuous duty curve by an exponential decay function. The front and rear traction motors were lumped into a single component with appropriate map-multipliers. The single motor was connected to a dummy transfer case to maintain a common vehicle interface with the conventional drivetrain.

Battery Pack – The battery pack component was based on Saft VL30P LiON cell data. Maps of open circuit voltage, charging resistance and discharge resistance vs. state of charge and cell temperature were input, with appropriate map-multipliers for the number of cells in series and parallel. Round-trip energy efficiency of the battery (Figure 16) was found to peak around 60% state of charge, so this was used as the target value for the hybrid control system. The initial and target state of charge can be set to different values to explore the effect of changes in battery charge.

Hybrid Controller – The XM1124 differed from the M1113 in that the driver has no input to engine throttle, and instead actuates the traction motors. The engine/generator Power Generating Unit (PGU) operation is determined based on the traction motor and accessory loads, and the battery pack state of charge. The strategy implemented was for the PGU to provide power to meet propulsion and accessory loads when possible, modified by the difference between actual and target battery pack state of charge. This power offset is calculated as the energy equivalent of the battery state of charge "error", divided by a charging system time constant. Based on the desired PGU power, an all-speed engine governor set-point is changed to the point of best fuel energy conversion efficiency of the PGU (Figure 17). Since the generator is able to absorb as much power as the engine can produce, generator load is relaxed when the engine is required to accelerate to a higher speed. From Figure 17, it is apparent that high PGU efficiency is maintained at light loads, due to the good part-load efficiency characteristic of diesel engines. For this reason an engine shut-off was not implemented.

Common Vehicle Components – A common GT-Drive vehicle model is used for both HMMWV variants. Common components include the vehicle body, and final-drive from the transfer-case or traction motor to the wheels. The vehicle body includes the mass, frontal area and aerodynamic drag coefficient. Rolling resistance and aerodynamic drag is based on a high-speed coast-down test of an M1113 HMMWV. The vehicle interacts with road and environment components, controlled by a PID driver actuating the accelerator and brake. The road component specifies either a fixed grade or a grade vs. distance profile from a library of standard Army test courses. The paved-road rolling resistance is modified by scaling factors for gravel and dirt courses based on SAE-J2188. The driver component can be given a constant speed target, or a speed vs. distance profile, to duplicate proving ground test procedures.

Powertrain Validation - The GT-Drive M1113 conventional and XM1124 Hybrid HMMWV models were validated against vehicle test data from the HEVEA program, and prior qualification tests for the M1113. Full throttle acceleration, gradeability, road-load fuel consumption and fuel economy on three standard Army courses were evaluated. Results for fuel economy on the Churchville-B off-road course are shown as an example (Figure 18). Once the GT-Drive vehicle model was validated, a separate powertrain model was prepared to interface with the SimCreator® vehicle model and human driver.

TEST DRIVER POWERTRAIN FEEDBACK - Army test-driver feedback on the realism of the powertrain models was favorable overall. The drivers pointed out a low coasting deceleration rate, which made maintaining the target speed difficult. For the M1113 converter-lockup on coast (zero throttle) was implemented to provide engine braking in all gears. A coefficient of performance converter map could also have been used to provide torque feedback in the overrunning range. For the XM1124 a small base level of traction motor regeneration was activated on coast, even without any brake-pedal actuation. Vehicle coasting behavior had not been a factor in the GT-Drive vehicle simulations, as the PID driver has very rapid response and is always applying either accelerator or brake. Other issues raised

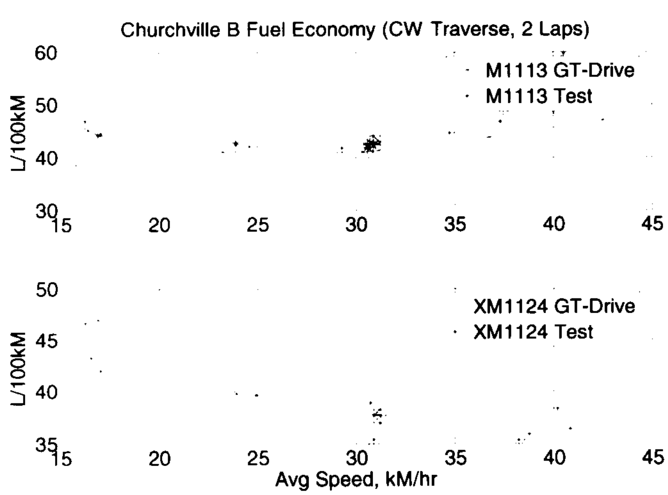

Figure 18. Fuel consumption results of model vs. field measurements. (top) Conventional M1113, (bottom) hybrid electric XM1124.

were the lack of neutral in the M1113, requiring the driver to use the brakes to hold the vehicle against converter stall-torque. A reverse gear was also desired, which is not required for the GT-Drive vehicle simulations. These features have been incorporated in subsequent models.

POWER SYSTEM INTEGRATION

POWERTRAIN INTERFACE - To prepare the GT-Drive powertrain models for interface with SimCreator®, the vehicle body, driver, road and environment components are removed. The driveline is broken at the transfer case output, and connected to a component that sets a rotational speed boundary condition and senses the reaction torque. A wiring harness component is incorporated to handle data flow between GT-Drive®, SimCreator®, and the human driver. SimCreator® inputs the driveline rotational speed, and senses the torque output propelling the vehicle. Driver interfaces include accelerator and brake pedal position, and transfer-case range and transmission gear selection (M1113 only). Vehicle service brakes are not included in the GT-drive powertrain, but the brake signal activates traction motor regenerative braking for the XM1124. Data channels from the powertrain include engine rpm, fuel flow rate, and integrated cumulative fuel consumption. For the M1113 transmission gear and lockup clutch status are also output. For the XM1124 motor and generator currents and battery voltage and state-of-charge are also output. The stand-alone powertrains were exercised in GT-Drive using signal generators and monitors to verify correct operation before being compiled as Real-Time data files. Test runs for the SimCreator/GT-Drive co-simulation were then compared to the GT-Drive vehicle performance predictions before experiment runs were performed. The result of this conversion is a data file entitled "M1113RT.dat" or "XM1124.dat" which is then passed to the GT-Drive real-time library initialization function.

SIMCREATOR INTERFACE – Figure 19 shows the power train model as implemented in SimCreator®. All elements modeled upstream of the transfer case were captured in the GT-Drive® model, so the component in the red box is wholly modeled by GT-Drive. To integrate the GT-Drive into SimCreator, a component was created which accepts inputs and provides outputs from/to other components. This component as built is shown in Figure 20. Figure 21 shows a synopsized code listing behind the component. There we see that the real-time version of GT-Drive® is called as a C-Code function from SimCreator®. First GT-Drive® is initialized in the "INIT" section via the `gtstartup()` call passing in the appropriate "*.dat" file. Then once the simulation begins, the "UPDATE" section is periodically executed. In this section the variable `udum[]` is stuffed with data flowing from SimCreator®, `INPUTV(gtInp)[indx]`. The `gtadvance()` function internalizes these data and moves the simulation forward, integrating its own states. The `gtupdate()` function then moves GT-Drive data into the `ydum[]` array. Finally, this array is copied to the SimCreator® output connectors, `OUTPUT(gtOut)[]`.

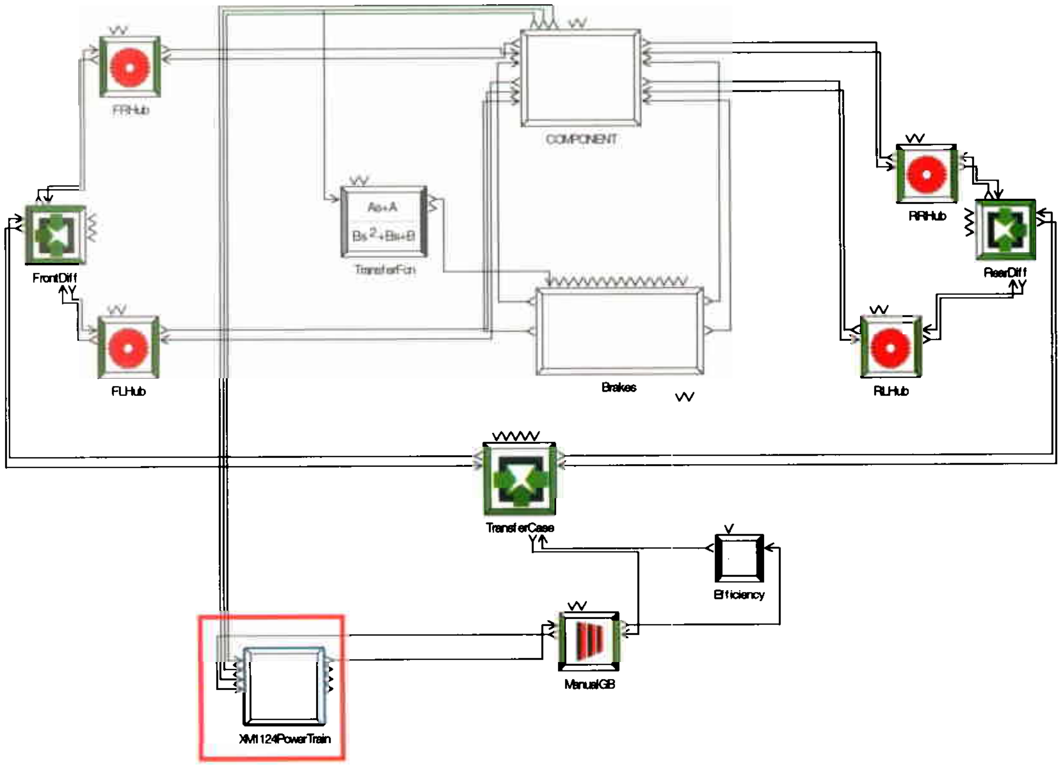

Figure 19. HMMWV Powertrain Model as represented in SimCreator®. Portion modeled in GT-Drive is shown in the red box.

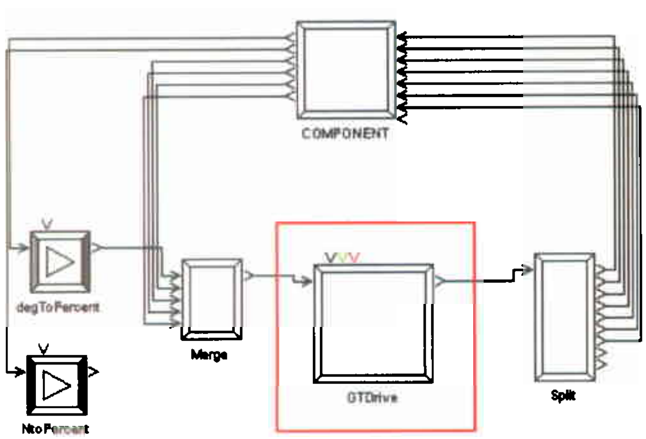

Figure 20. GT-Drive component as integrated into SimCreator®.

RESULTS

As mentioned earlier, the experiment was run for one week in which 166 data runs were recorded by two drivers. The actual set of completed runs is shown in Table 2. The participants in the experiment were two seasoned test drivers from APG. They were 58 and 44 years of age respectively. One reported 27 years of experience with the HMMWV, the other reported 1 year of experience. They had 42 and 28 years of experience driving automobiles. Both when asked about prior experience with motion sickness reported none, however, during the experiment runs both stated that they were experiencing symptoms. In order to mitigate these symptoms, most runs were completed with reduced motion gain. The amount of reduction depended on the severity of the course. The motion gain ranged from 10% to 100%. This reduced motion mitigated their symptoms and allowed them to continue with the experiment.

The initial fuel economy numbers derived from the runs on the RMS were regarded as preliminary data. In some cases they matched the measured field data fairly well, in others they did not. Included here are plots which depict the fuel consumption vs. average course speed (Figure 22). In each of these plots field data recorded at APG are compared to those recorded on the simulator. The fuel consumption values for the field test are as computed and reported by APG. The DCE-TOP fuel consumption values are computed as total fuel consumed divided by the total distance traveled. The average speed is simply total distance divided by total time. In the case of the hybrid-electric vehicle, the fuel consumed had to be corrected to account for the energy stored in or depleted from the battery during the run. The correction was empirically determined to be

$$\Delta f = -F_{\mathrm{corr}}\left(\%SOC_{\mathrm{final}} - \%SOC_{\mathrm{initial}}\right)$$

where $F_{\mathrm{corr}} = 0.05407\,\mathrm{L}/\%$ for a net charge decrease and $F_{\mathrm{corr}} = 0.06369\,\mathrm{L}/\%$ for a net charge increase.

In Figure 22 it appears that the simulation model did better than the actual vehicle with regard to fuel consumption. The fuel consumption values are closest for the Harford Loop runs and differ the most for the Churchville B runs.

For the conventional M1113 runs it is clear that there are losses present in the actual vehicle which are not present in the simulation model, thus producing better fuel consumption numbers for the simulator. For the

```
#include "gtfuncrt62.h"

BEGIN_DEFINITIONS
    DEFINE_INPUTV( SimRealVar, gtInp, "GT Inputs",
        "-", SIDE1, LOCATION1, DIMA);
    DEFINE_INPUT( SimRealVar, UpdateRate, "dt",
        "sec", SIDE2, LOCATION1)
    DEFINE_OUTPUTV( SimRealVar, gtOut, "GT Outputs",
        "-", SIDE3, LOCATION1, DIMB);

    DEFINE_SMEM(long, nInp)
    DEFINE_SMEM(long, nOut)
    DEFINE_SMEM(SimRealVar, deltaTime)
END_DEFINITIONS

BEGIN_INIT
    SMEM(sample)=RegisterSample(INPUT(UpdateRate));
    SMEM(deltaTime)=INPUT(UpdateRate);
    SMEM(nInp) = DIMA; // 128
    SMEM(nOut) = DIMB; // 384

    long jrtmsg   =  0 ;
    long ireqcase = -1 ;
    double gtidur ;
    gtstartup( "M1113RT", 7, "GTdrive", 7,
        &ireqcase, &gtidur, &jrtmsg );
END_INIT

BEGIN_OUTPUTS
    if(CheckSample(SMEM(sample))){
        int i;
        long sldone = 0 ;
        long iadv   = 0 ;
        static double ydum[384];
        static double udum[128];

        for(i=0; i < SMEM(inpwidth); i++ ) {
            udum[i] = (double)INPUTV(gtInp)[i];
        }

        gtadvance( &SMEM(deltaTime), &SMEM(nInp),
            udum, &sldone, &iadv );
        gtupdate(ydum);

        for(i=0; i<SMEM(nOut); i++ ) {
            OUTPUT(gtOut)[i] = (SimRealVar)ydum[i];
        }
    }
END_OUTPUTS

BEGIN_STOP
    long sunflag=0;
    slclose(&sunflag);
END_STOP
```

Figure 21. Code listing of SimCreator® component integrating GT-Drive Real-Time.

XM1124 the fuel consumption values were slightly better for the model than for the actual vehicle as well. These differences are most pronounced for the Churchville B runs. Since Churchville B is by far the hilliest course these differences may be attributable to the downhill regeneration and battery charge strategy. The XM1124 regeneration and battery charge algorithms are manufacturer-proprietary information, so the XM1124 model attempted to mimic its performance based on observed behavior. In this approximation the powertrain always tries to achieve 60% SOC for maximum round trip battery efficiency. The SOC-leveling strategy seems to be more complex in the actual vehicle in that the final SOC is never consistently one value as it typically was for the simulation.

After the experimental runs were concluded and the raw simulator values were processed, it was determined that some driveline losses and accessory loads of the vehicles were underestimated. Given better values, the GT-Drive® model was updated and rerun in GT-Drive®. Two sources of speed were used for these runs; the first was fixed at the target (Fixed/Posted Speed) and the second was given by correlated speed and grade information recorded from the DCE-TOP experiment (RMS Speed). These were re-run for the Churchville B, Munson SFC and Harford Loop courses for both the XM1124 and the M1113. The results may be observed in Figure 23. Observe that the GT-Drive model's results are improved with fuel consumption predictions generally increasing. Also notice that the "RMS Speed" generally predicts higher consumption values than the "Fixed/Posted Speed" traces due to variability of the speed for the DCE runs. We may therefore conclude that actual driver behavior affects fuel consumption predictions.

CONCLUSION

This paper describes a human-in-the-loop motion-based simulator which was built to perform controlled fuel economy measurements for both a conventional and hybrid electric HMMWV. The HMMWV model featured chassis, suspension, and steering implemented in the SimCreator® modeling tool and the propulsion system was implemented in the GT-Drive® modeling tool. These two models were integrated and run in real-time for the experiment. The simulated vehicles were run on

Table 2. Run matrix for all runs. Both drivers completed each iteration.

	Perryman Paved				Harford Loop			Munson			Churchville		
Speed	M1113	XM1124			M1113	XM1124		M1113	XM1124		M1113	XM1124	
mph (kph)		50	60	80		50	80		50	80		50	80
10 (16.1)					X	X	X						
15 (24.1)					X	X	X						
20 (32.2)					X	X	X						
25 (40.2)					X	X	X						
30 (48.3)					X	X	X				X	X	X
35 (56.3)					X	X	X	X	X	X	X	X	X
40 (64.4)								X	X	X	X	X	X
45 (72.4)					X	X	X	X	X	X	X	X	X
50 (80.5)					X	X	X	X	X	X	X	X	X
55 (88.5)					X	X	X	X	X	X	X	X	X
60 (96.6)					X	X	X	X	X	X	X	X	X

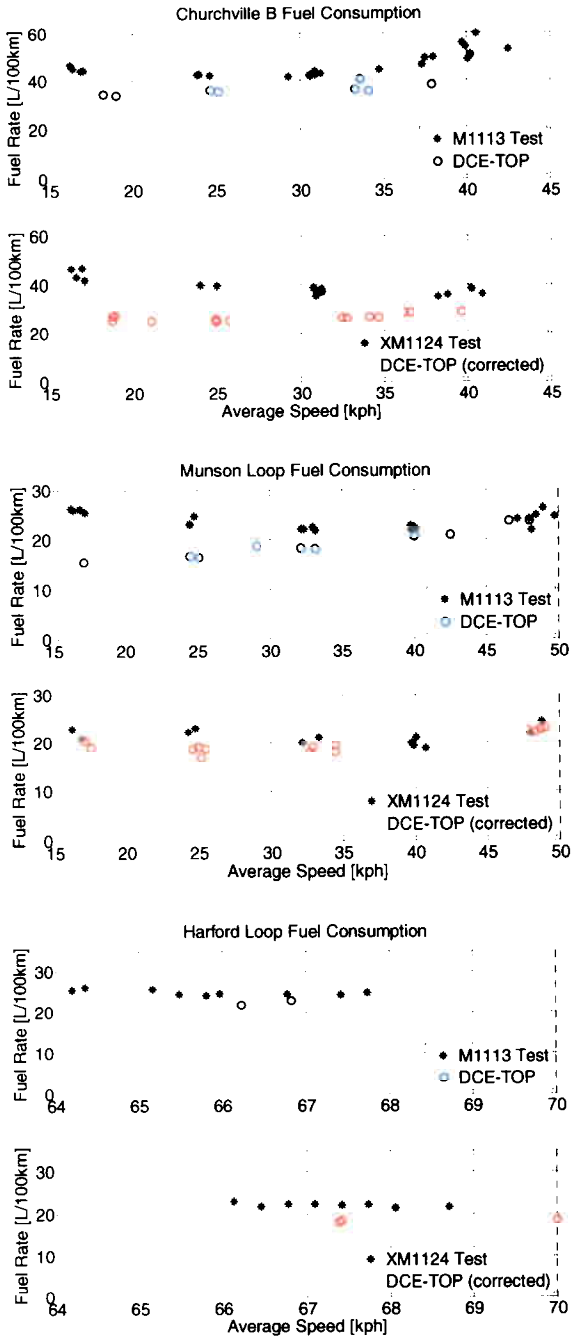

Figure 22. Fuel consumption plots from field tests at APG (stars) and DCE-TOP simulation runs (circles). Churchville B (top pair), Munson SFC (middle pair) and Harford Loops (bottom pair) are shown. Conventional (top subplot) and hybrid (bottom subplot) are shown. Hybrid values have been corrected for change in SOC. (For fuel consumption, lower values are better.)

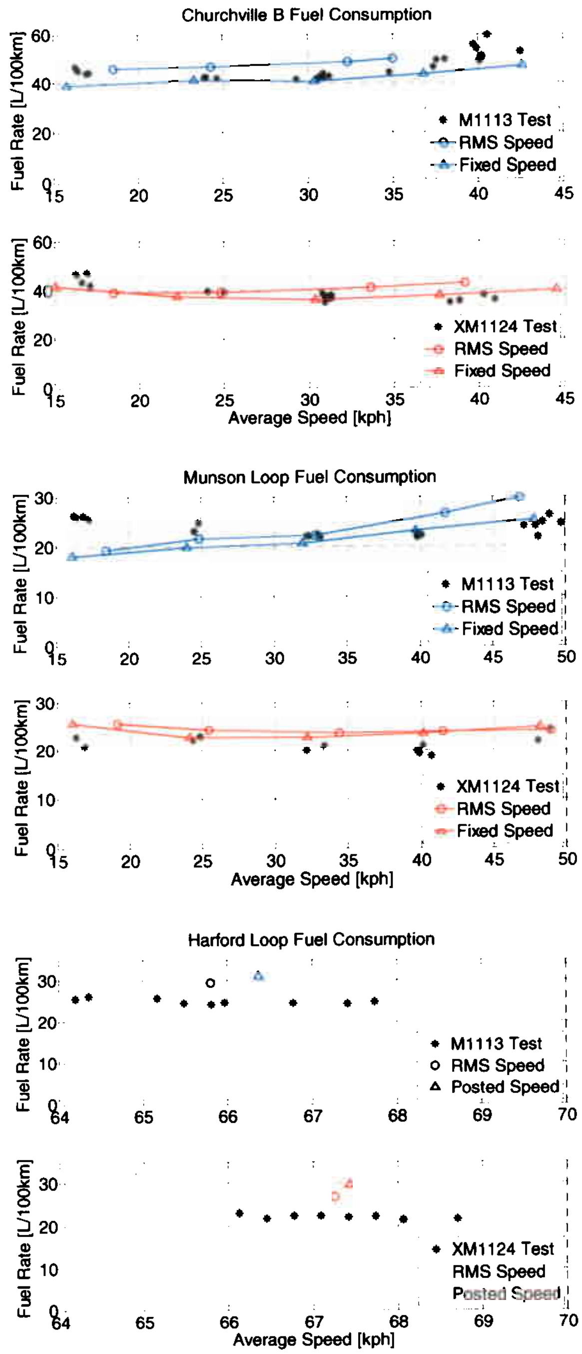

Figure 23. Fuel consumption plots from field tests at APG (stars) and improved GT-Drive bench runs (triangles and circles). 'RMS Speed' indicates speed command derived from the DCE-TOP experiment. 'Fixed/Posted Speed' indicates constant or piece-wise constant speed.

four different standard Army fuel consumption courses at varying speed. Experiments were performed with two experienced proving ground drivers. The paper concludes with a description results from the simulator test compared with field data. Although the simulator results in general produced better (lower) fuel consumption values than the corresponding field test, the 166 captured duty cycles (throttle, brake, steer, speed, grade) were used to improve the fuel consumption estimates with a refined version of the GT-Drive power train model. Such recorded use history was demonstrated to produce different estimates than using a fixed speed controller.

REFERENCES

1. Aardema, J., "Failure Analysis of the Lower Rear Ball Joint on the High-Mobility Multipurpose, Wheeled Vehicle (HMMWV)", Technical Report No. 13337, U.S. Army TARDEC, Warren, MI, Aug 1988.

2. U.S. Army Test and Evaluation Command, "Vehicle Test Facilities at Aberdeen Proving Ground", TOP 1-1-011, Aberdeen proving Ground, MD, 6 July 1981.
3. U.S. Army Test and Evaluation Command, "Vehicle Fuel Consumption", TOP 2-2-603, Aberdeen proving Ground, MD, 4 Feb 1986.
4. Brudnak, M.; Nunez, P.; Paul, V.; Mortsfield, T.; Shvartsman, A.; Perera, H.S.; Smith, W.; Mohammad, S.; Pozolo, M., "Human-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment 1", Paper SIW-06S-080, SISO, Orlando, FL, April 2006.
5. Brudnak, M.; Pozolo, M.; Paul, V.; Mohammad, S.; Smith, W.; Compere, M.; Goodell, J.; Holtz, D.; Mortsfield, T.; Shvartsman, A., "Soldier/Hardware-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment 2," Paper SIW-07S-016, SISO, Norfolk, VA, March 2007.
6. C. Ciesla, R. Keribar, T. Morel, "Engine/Powertrain/Vehicle Modeling Tool Applicable to All Stages of the Design Process", SAE 2000 Congress, Paper 2000-01-0934.
7. Paul, V.; Brudnak, M.; Ueda, J.; Shvartsman, A., "Simulation-based Hybrid Electric Combat Vehicle Duty Cycle Measurement", Intelligent Vehicle Systems Symposium, NDIA, Traverse City, MI, June 2006.
8. Perera, H.S., Romano, R. and Nunez, P., "Automated Methods for Converting a Non Real-time Cartesian Multi-body Vehicle Dynamics Model to a Real-time Recursive Model", SAE Technical Paper Series, April 2006.
9. Romano, R.A., "Realtime Driving Simulation Using A Modular Modeling Methodology", Paper 2000-01-1297, SAE, March 2000.
10. Romano, R.A., "Real-Time Multi-Body Vehicle Dynamics Using a Modular Modeling Methodology," Paper 2003-01-1286, SAE, March 2003.
11. Romano, R. and Schultz, S., "Validation of Real-Time Multi-Body Vehicle Dynamics Models for Use in Product Design and Acquisition", Paper 2004-01-1582, SAE March 2004.

CONTACT

Dr. Mark J. Brudnak
U.S. Army RDECOM-TARDEC
AMSRD-TAR-N/157
Warren, MI 48397-5000
586-574-7355
mark.brudnak@us.army.mil

ACRONYMS

APG: Aberdeen Proving Ground.
ATC: Aberdeen Test Center.
BUC: Built-Up Cab.
DADS®: Dynamic Analysis and Design System.
DCE: Duty Cycle Experiment.
GVW: Gross Vehicle Weight.
HEVEA: Hybrid Electric Vehicle Experimentation and Assessment.
HMMWV: High Mobility Multi-purpose Wheeled Vehicle.
MTA: Munson Test Area.
P&E: Power and Energy.
PGU: Power Generating Unit.
RMS: Ride Motion Simulator.
SFC: (Munson) Standard Fuel Course.
SOC: State of Charge.
TARDEC: Tank Automotive Research, Development, and Engineering Center.
TOP: Test Operating Procedure.